Thermal Control of Mars Lander and Rover Batteries and Electronics Using Loop Heat Pipe and Phase Change Material Thermal Storage Technologies

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ABSTRACT

This paper describes a novel thermal control system for future Mars landers and rovers designed to keep battery temperatures within the −10 °C to +25 °C temperature range. To keep the battery temperatures above the lower limit, the system uses: 1) a phase change material (PCM) thermal storage module to store and release heat and 2) a loop heat pipe (LHP) to transfer heat from a set of Radioisotope Heater Units (RHUs) to the battery. To keep the battery temperature below the upper limit, a thermal control valve in the LHP opens to redirect the working fluid to an external radiator where excess heat is dumped to the atmosphere.

The PCM thermal storage module was designed and fabricated using dodecane paraffin wax (melting point, − 9.6 °C) as the phase change material. A miniature ammonia loop heat pipe with two condensers and an integrated thermal control valve was designed and fabricated for use with the PCM thermal storage unit. The results from an ongoing experimental simulation of the Mars '03/'05 rover thermal performance in the Martian environment are described in the paper. The tests were performed for various internal configurations of the PCM and LHP arrangements in worst-case hot and cold environment. Based on the results of these tests, the Mars '03/'05 rover thermal design development will be finalized. Many lessons already have been learned during the development and implementation of these thermal technologies for Mars rover battery thermal control and recommendations for the design and operation of loop heat pipe and phase change material thermal energy storage systems for future space missions are made herein.

INTRODUCTION

One of the challenges to the long-term survival of Mars landers and rovers is the effective thermal control of their batteries and electronics. The thermal environment on Martian surface is harsh, with nighttime temperatures dropping as low as −100 °C and the daytime temperatures rising slightly above 0 °C. Without a proper thermal control design, the battery and electronic temperatures in landers and rovers can drop down to − 60 °C at night and rise up to 60 °C during daytime operations. Batteries will freeze and fail at these low temperatures, and electronics will fatigue and fail when subjected to these repeated wide temperature swings. After successfully operating 83 Martian days, the Mars Pathfinder lander ceased communications with the Earth, primarily because the rechargeable batteries failed.

The thermal control of Mars landers and rovers in the past utilized passive techniques such as high performance thermal insulation, electrical heaters and the radioisotope heater units (RHUs). This passive design successfully protected the batteries and electronics inside the lander/rover from going below their temperature limits at night; however, daytime operations were limited to keep internal heat dissipation from causing excessive temperatures inside the thermal enclosure. Battery mass is driven by the need for nighttime power dissipation inside the thermal enclosure to keep the battery and electronics warm. Excessive battery mass will limit allowable science payload.

Future Mars missions are expected to carry more science equipment (which will dissipate a larger amount of heat) and to conduct more aggressive, longer duration science experiments. Past passive thermal control techniques severely limit the operation and also the long-term survivability of the mission. The key design drivers of thermal control systems for future Mars missions are: 1) to maintain the equipment inside above the minimum allowable temperature at night; 2) to minimize the heater power required at night; 3) to reduce the magnitude of temperature cycles experienced by the inside electronics during Martian diurnal cycles; 4) to develop a thermal design that is simple and at the same time robust; and 5) to accommodate long duration high power dissipating operational scenarios without exceeding maximum temperature limits. These requirements have necessitated developing novel thermal control

approaches employing advanced thermal control technologies such as lightweight high performance thermal insulation, miniature loop heat pipes (LHP), and phase change material (PCM) thermal storage devices (Reference 1).

Of all the equipment used on Mars vehicles, batteries are the most temperature sensitive. Rechargeable batteries can age prematurely at elevated temperatures (above 40 °C) and electrolytes can freeze at low temperatures (below −30 °C). A novel concept for thermal control of batteries using phase change material thermal storage and a miniature variable conductance LHP technologies was developed for the Mars '03/'05 rover (Figure 1). These two technologies are also being investigated for use in battery thermal control on future Mars landers and rovers. The development of these two technologies and their experimental evaluation for the Mars '03/'05 rover in a simulated Mars environment are described in this paper.
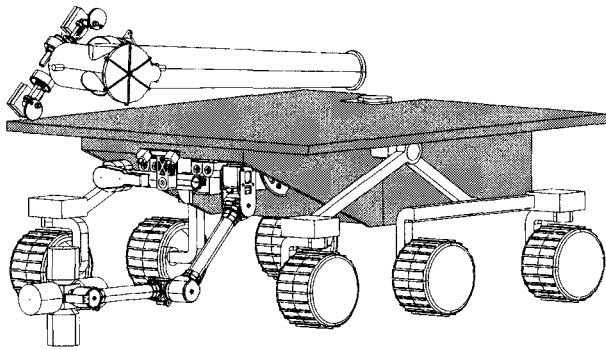

Figure 1. A Drawing of Mars '03/'05 Rover

MARS ROVER/LANDER BATTERY THERMAL CONTROL USING ADVANCED TECHNOLOGIES

The use of lithium ion secondary batteries is planned for future Mars missions; the lower temperature limit of these batteries is −20 °C while the upper limit is 30 °C. The Martian diurnal environmental temperature varies from −100 C at night to 0 °C during the day (see Figure 2). The thermal control system must keep the batteries within their allowable limits in this environment. For the Mars '03 rover, RHUs provide the heat to keep the rechargeable batteries and electronics above their minimum allowable temperature limits at night.

The new thermal control concept for the rover batteries uses a variable conductance miniature LHP to transfer heat from the RHUs to the batteries (see Figure 3). Throughout most of the day and all through the night, the LHP transfers RHU heat to the battery. The flow path from the thermal control valve to the radiator is closed and all of the flow bypasses the radiator. However, during a short period in the afternoon, when the ambient atmosphere is relatively warm and the electronics inside the rover are operating at full power, the battery

temperature may exceed 30 °C. During these periods, the thermal control valve opens and the vapor from the evaporator flows to the radiator, thus rejecting excess heat to the external environment.
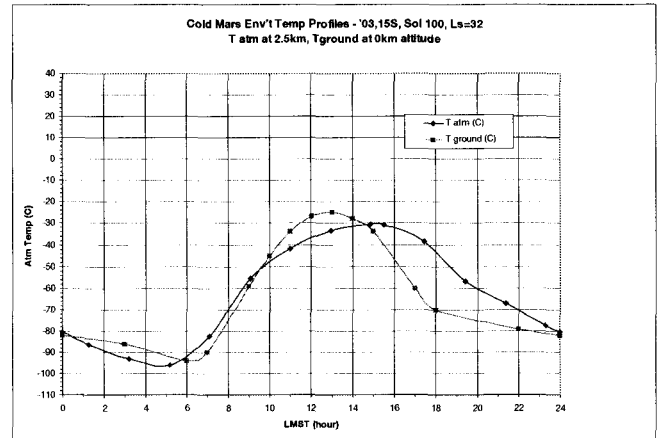

Figure 2. Worst-case Cold Martian Thermal Environment for Mars '03/05 Rover
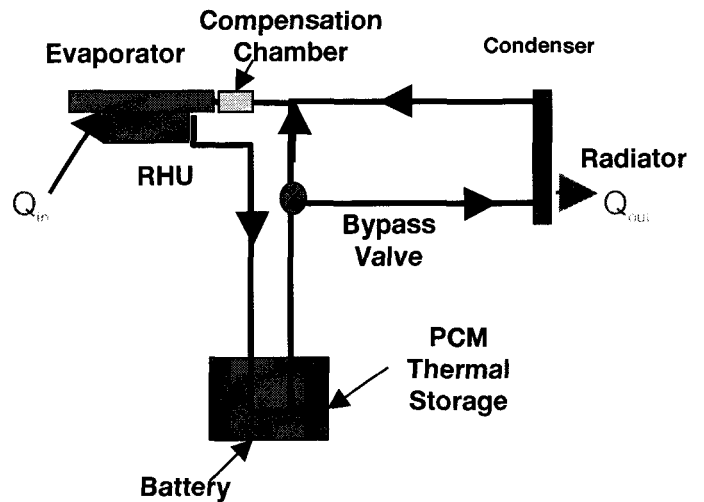

Figure 3. Mars Rover Battery Thermal Control Using Loop Heat Pipe and PCM Thermal Storage

In addition to the LHP, a PCM thermal storage is used to enhance the thermal capacity of the batteries and to keep them above their lower temperature limit. The PCM melting point temperature is close to the battery lower temperature limit; it greatly reduces the amount electric heater power needed to keep the battery above −20 °C at night. Moreover, the combined use of the LHP and PCM technologies allow the batteries to be maintained within their allowable temperature on Mars using fewer RHUs. Furthermore, the need for additional electric heater power for the battery to maintain its temperature above −20 °C is reduced, thus reducing size and mass of the battery required by the rover.

VARIABLE CONDUCTANCE LOOP HEAT PIPE

The LHP was originally developed in the former Soviet Union and since has flown in several Russian spacecraft. It also is increasingly being used in Earth orbiting spacecraft and communication satellites (References 2-4). LHPs are two-phase passive heat transfer devices that use capillary action of a wick structure in the evaporator. Unlike fixed conductance heat pipes where the capillary groves or the wick are located along the entire length of the pipe, the main wick in the LHP is located only in the evaporator. The LHP consists of four major elements: 1) an evaporator where heat is collected by the working fluid, changing its phase from liquid to vapor; 2) a condenser where the vapor condenses and releases heat; 3) a compensation chamber (CC) where the excess working fluid is stored, and 4) the transfer tubes which carry the vapor from evaporator to the condenser and carry the condensed liquid back from condenser to the evaporator through the CC.

Typically LHPs use a heater on the CC to control the conductance between the evaporator and the condenser. By keeping the CC warmer than the evaporator, the LHP operation can be turned off even when the condenser is at a temperature well below the evaporator. The availability of the heater power on Mars at night is restricted by the size of the battery. This restriction led to the development of a variable conductance loop heat pipe (VCLHP) with a pressure actuated passive thermal control valve which allows the conductance between the evaporator and the radiator to be varied. This type of LHP was first designed and used on the Russian Mars '96 mission for the thermal control of the penetrator payload (Ref. 5). The thermal control valve (see Figure 4) operates based on the backpressure provided by nitrogen gas on one side of a metal bellows in the valve. The other side of the bellows is open to the ammonia vapor used in the LHP. This bellows actuates a rod that either opens or shuts a port connecting to the radiator. The backpressure on the bellows is set to a pressure corresponding to the saturation pressure of ammonia at the desired battery upper temperature limit. When the battery temperature rises above this temperature, the bellows expands which moves the actuating rod to open the port to the radiator and to close the bypass path.

The VCLHP was designed and fabricated by the Dynatherm Corporation of Hunt Valley, Maryland for JPL in June 1999. A picture of the VCLHP is shown in Figure 4b. The total mass of the unit including the radiator is less than 700 g. This unit was integrated with the PCM thermal storage unit and rover battery thermal control experiment in October 1999 for experimental evaluation at JPL. The LHP design was based on a single CC. The LHP is designed to operate in a power range from 3 Watts to 40 Watts and an evaporator temperature range from –20 °C to 50 °C. The rover operation on Mars would involve various orientations where the CC may be below the evaporator since the

rover can climb over rocks and up slopes that can put it at a 45° angle to the horizontal. The secondary wick between the CC and evaporator is usually weaker and does not provide enough capillary head to transfer liquid to the evaporator when the CC is located below it in a 1-G environment. For such operations, generally two CCs are used so that one CC is always at or above level of the evaporator (Ref. 5). Only one CC is used in the VCLHP designed for this application since the LHP operations involve low power (about 10 Watts) and the secondary wick was designed strong enough to support this level of power during adverse CC orientations. The specifications for the VCLHP are given in Table 1.

To the Comp. Chamber

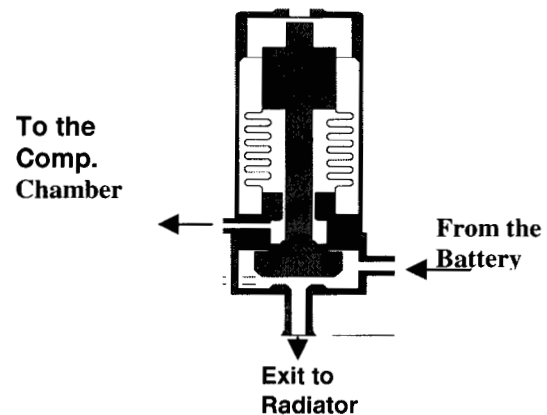**From the Battery**

Exit to Radiator

Figure 4a. Schematic of Variable Conductance Loop Heat Pipe Three-Way Thermal Control Valve
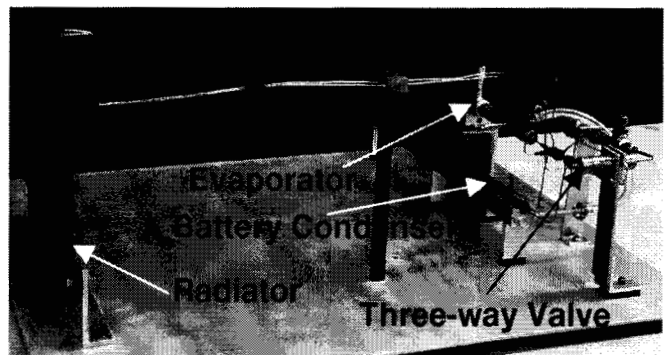

Figure 4b. Photograph of the Miniature Variable Conductance Loop Heat Pipe

The key issues related to using a VCLHP for rover battery thermal control are: 1) LHP start up and operation at low power, 2) LHP operation in gravity environment with the CC below the evaporator, and 3) operation of the thermal control valve to maintain the battery temperature. The rover battery thermal control test setup allows testing in all of these conditions.

Table 1. Specifications for Variable Conductance Loop Heat Pipe for Mars Rover Battery Thermal Control

Component	Description
Evaporator	Aluminum 6063, 0.5" ID, 4" long
Primary wick	Sintered Nickel, 1.2 micron pore size
Compensation Chamber	304L Stainless Steel
Transport Lines, Condenser	304L Stainless Tubing, 1/16" X 0.012" wall
Vapor	75" long
Liquid	25" long
3-Way Valve	3 cm³
Ammonia	12 g, 99.998% pure

PHASE CHANGE MATERIAL THERMAL STORAGE

A PCM thermal storage unit was designed and fabricated for use with the VCLHP. The PCM is dodecane, which has a melting point of –9.6 °C and a heat of fusion of 217 J/g. A thermal storage enclosure containing this PCM was designed so that the batteries can be housed inside. Energy Science Laboratory Inc., (ESLI) of San Diego, California, designed and built the unit in late 1998 to JPL's specifications. Typical challenges in using PCM thermal storage are the poor thermal conductivity of the PCM in its solid phase, containment of the PCM in leak-tight container that can handle expansion and contraction during the freeze-thaw process, and minimizing the mass of the PCM system. Several novel features were used in the design and fabrication of the PCM storage unit. A carbon fiber core used to provide the PCM with a good thermal conductivity in its solid phase also provided structural strength to the module. Thin-walled aluminum sheets were used to build the container. The construction of the unit used structural epoxies to bond the various container parts. A photograph of the PCM thermal storage unit is shown in Figure 5; the specifications are given in Table 2.
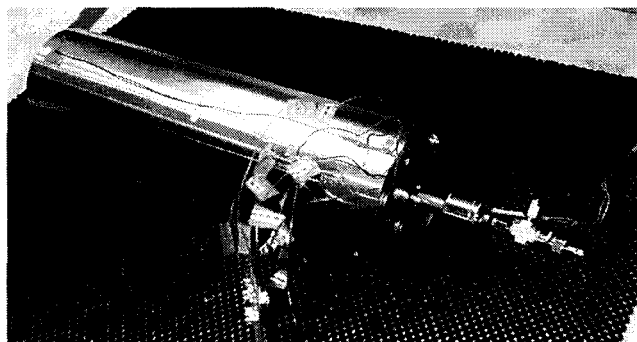

Figure 5. Photograph of Phase Change Material Thermal Storage Unit for Battery Thermal Control (the ends of four batteries inside the unit are also visible)

Table 2. Battery Thermal Control PCM Thermal Storage Specifications

PCM Storage Unit Component	Description
Thermal storage unit dimensions	35 cm long, 9.5 cm OD
Mass of component	Carbon fiber core, 80 g; Dodecane, 530 g; Aluminum walls caps, 175 g
Dodecane thermal properties	Melting point, -9.6 °C; Heat of fusion, 217 J/g; Density at 65 °C, 0.72 g/cm³

The total mass of the unit is about 800 g, with 66% of the mass consisting of dodecane. The latent heat capacity of this unit is 32 Watt-hours. The unit was tested for its performance to verify the thermal capacity of the unit at the specified temperature. The test results corresponded with the latent heat of the dodecane material contained in the unit. Further, the unit was subjected to seven thermal cycles from –60 °C to 60 °C to verify its integrity. A typical thermal cycle is shown in Figure 6; note the horizontal temperature/time characteristics during the melt (t=200 to t=360 minutes) and freeze (t=800 to 960 minutes).
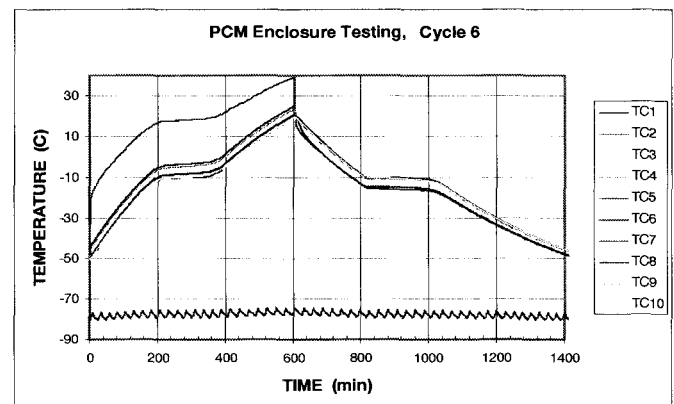

Figure 6. Typical data from Ten Thermocouple Located on the PCM Unit during Temperature Cycling Test

Some of the issues that needed to be investigated for the PCM thermal storage application for the rover battery thermal control were: 1) how readily the PCM freezes and melts with the removal or addition of the heat, 2) how conductive is the thermal interface between the storage unit and the batteries, and 3) how well the PCM storage helps the batteries stay above –20 °C during the Martian diurnal cold environment during the Mars'03 mission.

TEST EQUIPMENT SETUP

The purpose of these tests was to see how well the battery thermal control concept worked in a realistic Martian environment, and the tests were conducted in the Thermal Technology Laboratory at JPL. The key elements of the thermal control system, the VCLHP and the PCM thermal storage unit, were integrated with other hardware simulating parts of the rover vehicle. Film heaters wrapped around aluminum cylinders simulated the rover batteries and were inserted in the PCM storage unit. The PCM and the VCLHP were enclosed in an aluminum box simulating the rover warm electronics box (WEB). Then, the temperature of this box could be controlled using film heaters and a heat exchanger plate to simulate the Martian environment experienced by the rover WEB. The VCLHP radiator was located outside of the aluminum box, and its temperature could also be controlled to simulate the Martian environment using a liquid nitrogen heat exchanger plate. The thermal control system and simulated rover vehicle hardware were securely mounted to an aluminum base plate and instrumented with 40 type-E thermocouples. The thermal control system, the simulated rover vehicle hardware, and the support equipment are all shown schematically in Figures 7a and in a photograph in 7b.
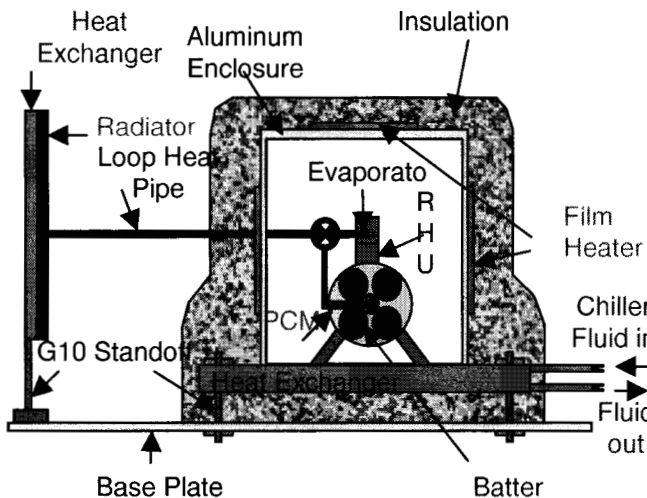

Figure 7a. Test Setup Schematic for the Evaluation of LHP and PCM Thermal Storage Technologies for Rover Battery Thermal Control

These tests also required some support equipment. A universal balance supported the base plate and allowed changes in hardware orientation to observe the effect of LHP orientation on its operation. Of particular interest was the orientation of the compensation chamber with respect to the evaporator. A chiller cooled/warmed the methanol circulating through the rover WEB simulator heat exchanger, and the flow rate of the methanol was measured using a turbine flowmeter. A liquid nitrogen dewar system cooled the external rover radiator down to the temperatures expected on Mars. An instrument rack housed all the electronic equipment, including power supplies, temperature data loggers, and heater power

controllers. A dry gaseous nitrogen purge system with a mylar bag enclosed the entire test setup whenever the test temperatures were below 15 °C to prevent condensation on the test hardware.
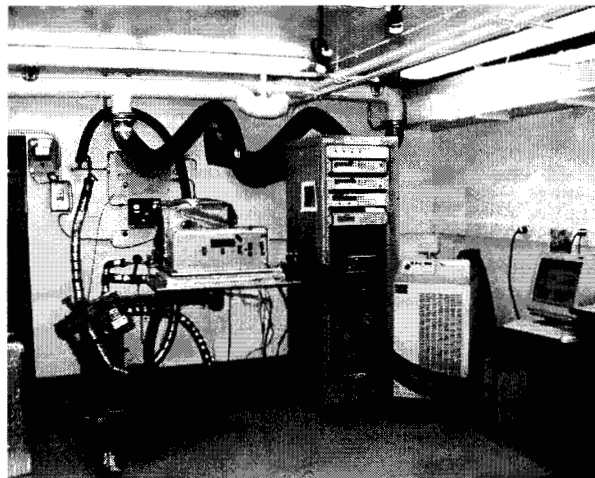

Figure 7b. A Photograph Showing the Test Setup

A PC running a program within LabView was used to monitor the thermocouple temperatures, heater powers, and methanol flow rate during the test. It also was used to control the simulated WEB and VCLHP radiator temperatures and the battery and RHU heater powers during the test. These parameters were set directly from the front panel of the LabView program during the tests; a screen image of the front panel is shown in Figure 8. Note how the thermocouple temperatures and heater powers are superimposed on a hardware schematic. Not only does the program allow continuous monitoring of forty thermocouples installed at various locations on the hardware, but it also allows viewing of the thermocouple data. In other words, it was possible to select a group of thermocouples and display the temperature-time history for any time or temperature range while the program continued to run.
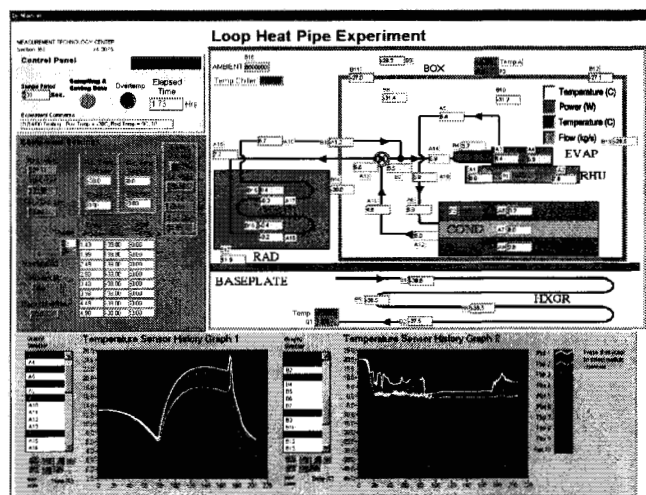

Figure 8. Screen Image of LabView Program Front Panel Used to Control Test Operating Conditions to Monitor and Examine Data in Real Time

TEST RESULTS AND DISCUSSION

At the time of writing this paper, extensive testing of the VCLHP without the PCM thermal storage was completed whereas only limited testing has been conducted with the PCM thermal storage. Only the results from the tests conducted between November 1999 and March 2000 are reported in this paper; additional tests are in progress.

The four major types of tests conducted so far were the following.

1. Low power operation of LHP and determination of minimum heater power for start up,

2. Thermal control valve operation at different valve set point temperatures,

3. LHP operation at various adverse orientations of the evaporator with respect to the CC and condenser, and

4. Diurnal simulation of battery thermal control under worst case hot and cold conditions.

LOW POWER OPERATIONS

The power level at which the LHP is operated in the rover battery thermal control is low (5 Watts to 7 Watts); therefore, one of the objectives was to see how well the LHP starts and operates at low power levels. In the first series of tests, the LHP was operated at several low power levels (3, 5, 7, 10, and 15 Watts) with the radiator maintained at 15 °C, 0 °C, and –30 °C. The insulated evaporator was kept at lab ambient environment. The compensation chamber was at the same elevation as the evaporator while the radiator was in the vertical position.

The LHP easily started at power levels above 3 Watts. At 3 Watts, it did not start consistently. For power levels of 5 Watts and higher the start was consistent at all radiator temperatures. An additional start-up heater power of 3 Watts would ensure the start of the LHP for all situations. Once the LHP has started, the startup heater can be turned off and the LHP will continue to operate normally.

At low power operations, less than 10 Watts, the temperature of liquid returning to the compensation chamber oscillates suggesting a chugging flow for radiator temperatures of 0 °C and above. These oscillations typically had an amplitude of 3 °C and a frequency of five cycles per hour. Figure 9 shows the evaporator and liquid return temperature for the LHP operation at 3 Watts. These oscillations are absent when the radiator temperature is –30 °C.

The low power start and operations of the current LHP need to be improved. The modifications planned for a future miniature LHP will reduce the thermal conductance between the evaporator and the compensation chamber. The thermal driving potential to drive the loop is the temperature difference between the CC and the evaporator. If the CC is not sufficiently isolated from the evaporator, it takes a larger power at the evaporator to cause the loop to start. Design modifications are currently being investigated for future miniature loop heat pipes.
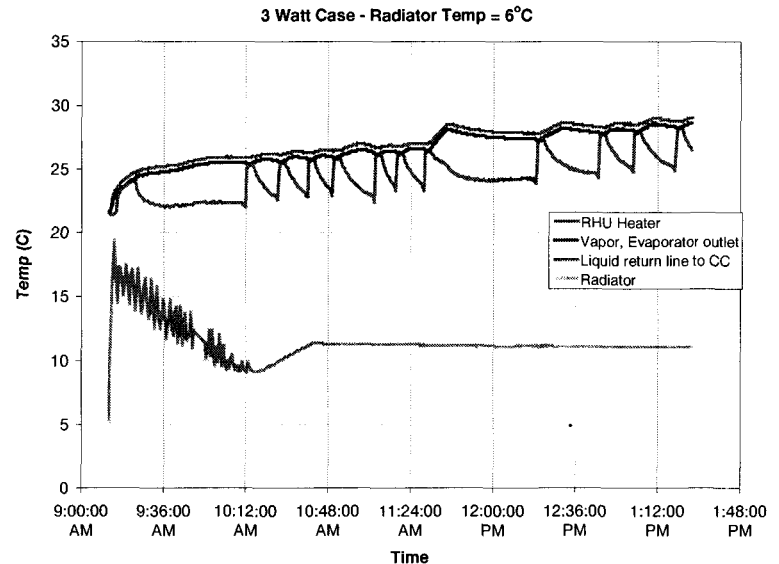

Figure 9. Temperatures Data from Low Power Operation of the Variable Conductance Loop Heat Pipe

THERMAL CONTROL VALVE OPERATIONS

The valve set point temperature can be set to any value by adjusting the valve backpressure. The backpressure is maintained by gaseous nitrogen, which is filled in the gas side of the valve (see Figure 3). The gas pressure is set at the saturation pressure of ammonia at the desired set point temperature. These tests varied the backpressure when the LHP was operating under a constant power. The evaporator temperature at various backpressures is shown in Figure 10.

One of the major test objectives was to see how well the three-way thermal control valve controlled the battery temperature. The valve functioned well in opening and closing the bypass to the radiator. However, the temperature at which it actuated was approximately 10 to 15 °C off from the set point associated with the backpressure of the gas. This is attributed to the spring constant associated with the bellows of valve and onther unknown effects, and is not a major concern as it can be corrected to some extent. For other applications requiring more precise temperature control, on the order of 1 to 3 °C, the current VCLHP with the valve in the vapor line may not be the suitable choice for the low power operation. During the diurnal simulation, the 3-

way valve functioned well and the changing environment did not affect the valve backpressure. At present, tests are being conducted using a CC heater to control the battery temperature. The drawback of this option is that power must be applied to the CC heater at night (when power is scarce) to keep the LHP from operating and lowering the battery temperature below the its low limit.

the power levels were varied from 10 to 45 Watts and the LHP operated without dry out. In summary, the LHP operated satisfactorily in adverse orientations for power levels below 40 Watts and it is expected to perform better in the reduced gravitational field on Mars (3/8 G). These results also show that there is no need to add a second CC to the LHP.
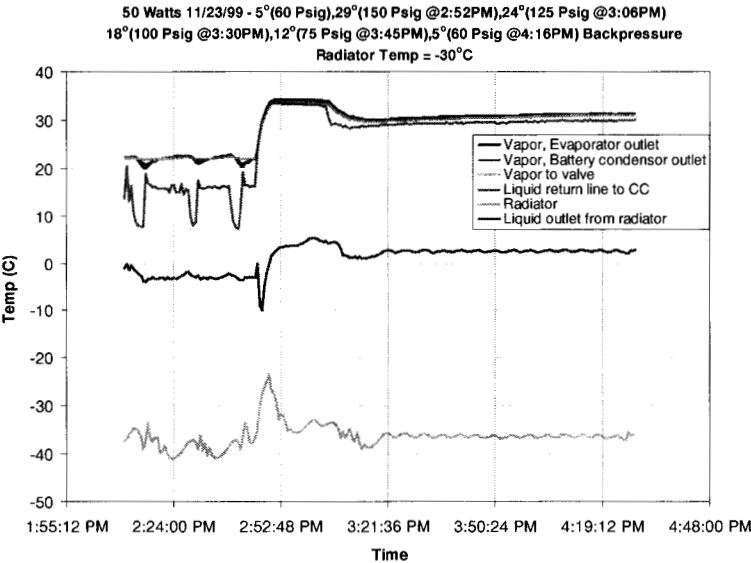
Figure 10. LHP Evaporator Temperatures at Various Backpressures of the Thermal Control Valve

Figure 11. LHP Temperatures for Adverse Orientations of Evaporator with respect to the Compensation Chamber

EVAPORATOR ADVERSE ORIENTATION

One advantage of the LHP is that it can operate well in adverse orientations in a gravitational field. The first adverse LHP orientation we consider is when the CC is at a lower elevation than the evaporator. In this orientation the weak secondary wick may not be able to draw the liquid from CC into the evaporator; therefore, it was important to verify whether an LHP with a single CC could operate this way. Tests were conducted with the CC below the evaporator at varying power levels to verify that the secondary wick could move additional liquid from the CC to the evaporator when required. The second adverse LHP orientation we consider is when the condenser is located at a lower elevation than the evaporator. Since it is well known that LHPs can pump liquid from the condenser to an evaporator located two meters above, this was not as important a concern.

The LHP performed well with its single compensation chamber in an adverse orientation with respect to its evaporator. It operated smoothly from 10 to 30 Watts, but it dried out at 40 Watts. The evaporator temperature data from this test is shown in Figure 11. The LHP did not start at lower power levels of 5 Watts or 7 Watts, but it started at 10 Watts and continued to operate at power levels of 20 Watts and 30 Watts. Evaporator dry out occurred at 40 Watts. In another test in this orientation,
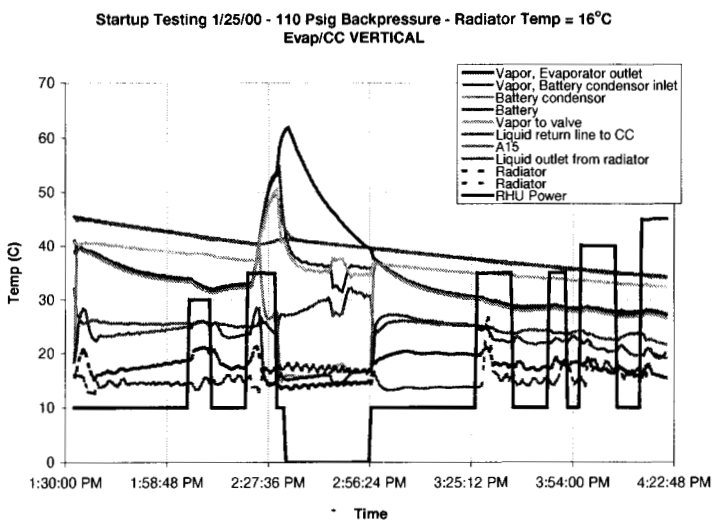
Several tests were conducted for the other adverse/favorable orientations where the evaporator is at a higher/lower elevation than the condenser/radiator. For these tests, the evaporator and the CC were in the same plane, but the condenser was in a plane at a lower or higher elevation. The evaporator temperatures for several power levels and radiator orientations are shown in Table 3. Note that the data in the third column is for the radiator in the evaporator/CC plane but in the vertical position. The radiator was maintained at 16 °C in all cases.

Table 3. Test conditions for the adverse orientation tests.

	Evaporator Temperature, °C		
Evaporator Power, Watts	Radiator (horizontal) above Evap/CC plane	Radiator (horizontal) below Evap/CC plane	Radiator (vertical) in the Evap/CC plane
5	37.6	37	28.8
10	27.7	40	29.4
20	20.6	44.5	27.6

The evaporator temperatures were greater for the adverse orientations because the LHP evaporator wick was pumping against the gravitational field. The results are consistent with expected LHP operation in adverse and favorable orientations of the evaporator with respect to the condenser in a 1-G environment.

BATTERY THERMAL CONTROL DIURNAL
SIMULATION

The simulated batteries and the thermal control system were tested in a simulated hot and cold diurnal Martian environment. This test was done by controlling the simulated rover WEB walls to diurnal temperature profiles predicted by an analytical thermal model of the rover operations for the Martian worst-case hot and cold conditions. The radiator temperatures were also maintained at the levels predicted by the rover analytical thermal model. These WEB wall and radiator temperature profiles for the hot diurnal test are shown in Figure 12. The PCM unit was not included the test results reported herein; however, it will be included in future tests. The diurnal tests were done at a 10 Watt power level to avoid the aforementioned 7 Watt low power operational problems.
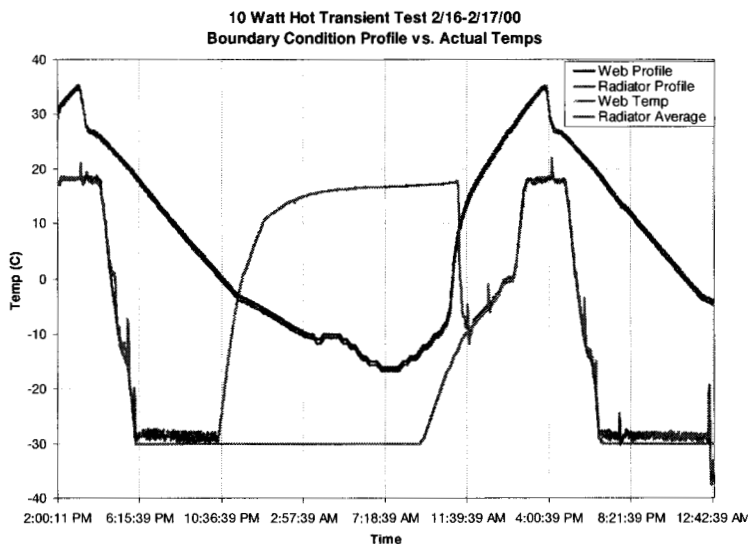
about 1 W/°C. In a plot of predicted and actual battery temperatures for this test is shown in Figure 14. The assumed LHP conductance at these power levels was 2 W/°C, higher than what was experienced in the test (1 W/°C).
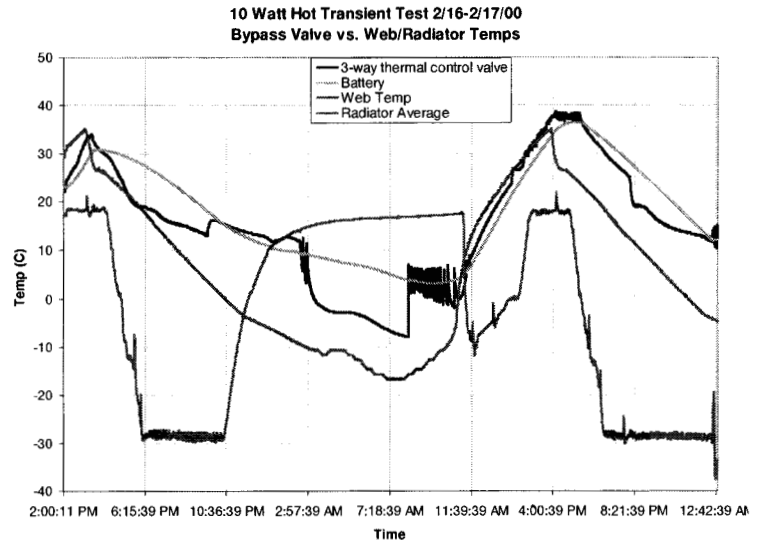

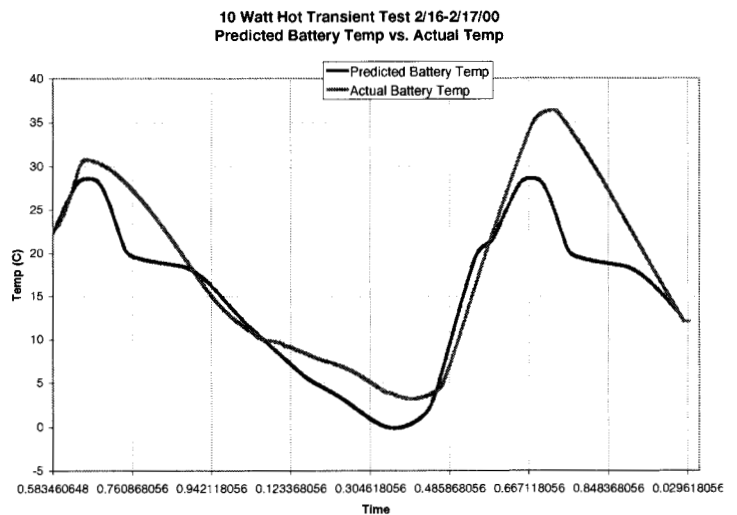Figure 13. Battery Thermal Control System Diurnal Temperature for the Worst Case Hot Conditions

Figure 12. Mars '03/'05 Rover WEB and radiator Diurnal Temperatures for the Worst Case Cold Conditions

Figure 14. Comparison of Actual and predicted Battery Temperatures for Worst Case Hot Conditions

For the hot diurnal case, the temperatures of the battery and other components are shown in Figure 13. The battery temperature goes as high as 36 °C, even though the valve backpressure was set to 110 psig, which corresponds to 20 °C ammonia saturation temperature. This is primarily due to three reasons. First, the opening of the valve occurs between 30 and 35 °C (after 4 PM). Second, the WEB wall temperature is rising at this point and transferring heat to the battery and the evaporator. Third, the conductance between the evaporator and the radiator is not very high at these low power levels. The conductance between evaporator and the radiator is

For the cold diurnal test case, the actual battery temperatures compare well with the predicted temperatures. Unlike in the hot diurnal case, the thermal valve is closed during the entire diurnal cycle. The RHU heat is always transferred to the batteries. The battery

temperatures go as low as -14 °C around 7 AM. A comparison of actual and predicted temperatures is shown in Figure 15. The small difference between the actual and predicted temperatures is due to lower LHP conductance values experienced during the test.
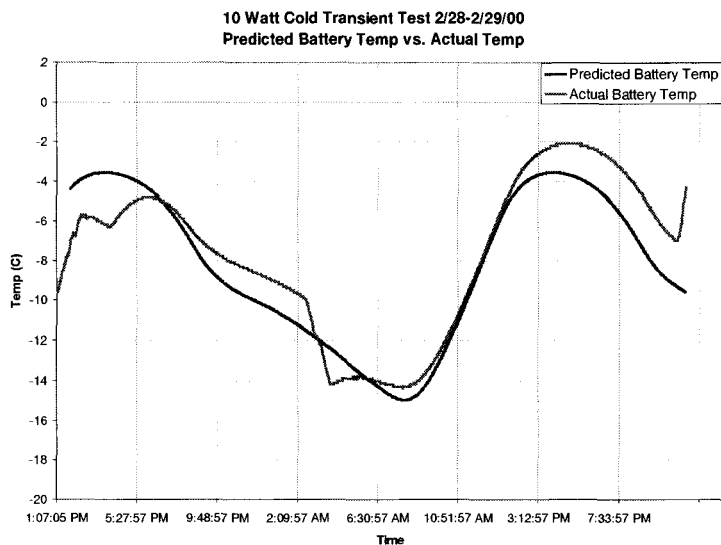
10 Watt Cold Transient Test 2/28-2/29/00
Predicted Battery Temp vs. Actual Temp

Figure 15. Comparison of Actual and Predicted Battery Temperatures for the Worst Case Cold Conditions

PCM THERMAL STORAGE PERFORMANCE

The tests conducted with the PCM storage unit so far have been steady state tests at fixed boundary conditions for the radiator and the rover WEB. Based on the test data, the thermal performance of the PCM unit in terms of heat transfer between the PCM unit and battery was satisfactory. The interface material used for heat transfer between the battery and the PCM unit works well and the temperature drop between the two was about 1 °C. The inclusion of the PCM with the battery would keep the battery above −10 °C during the worst case cold diurnal conditions on Mars.

An analytical simulation of the system with the PCM for the cold condition predicted the battery temperatures shown in Figure 16. Compared to the lowest battery temperature of −14 °C during the worst case cold diurnal case, the lowest battery temperature with the PCM is much above −10 °C. Thermal control diurnal tests with the PCM storage unit are planned to be performed later.

One of the disadvantages of using the PCM thermal storage is its mass; therefore, alternate methods of providing the heat to the batteries at night are considered. Alternate methods include using electric heaters on the battery or using additional RHUs. Electric heaters on the batteries would necessitate additional power and, therefore, a larger battery. If RHUs are used instead, the design must accommodate for the additional mass and cost of the RHUs. In addition, the RHUs would cause undesired daytime heating since they cannot be turned off during the daytime operations and warmer environment.
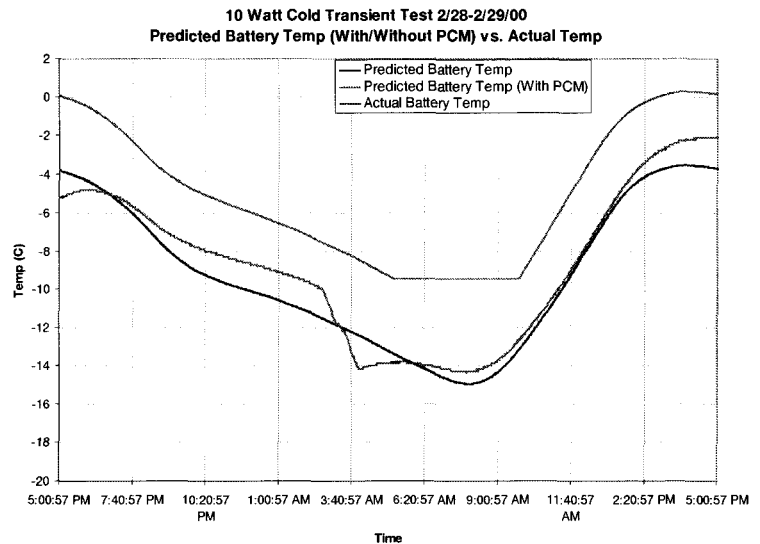
10 Watt Cold Transient Test 2/28-2/29/00
Predicted Battery Temp (With/Without PCM) vs. Actual Temp

Figure 16. Analytic Prediction of Diurnal Battery Temperature with and without PCM Thermal Storage

CONCLUSIONS AND RECOMMENDATIONS

Several conclusions can be drawn from the tests regarding the effectiveness of the VCLHP and PCM storage unit for Mars rover battery thermal control. The miniature VCLHP tested in the system exhibited following major characteristics.

1. At very low power operations, below 10 Watts, the LHP tended to run hot and with small oscillations in the evaporator temperatures. These oscillations occur for the radiator in both vertical and horizontal orientations. The LHP ran warmer due to a large conductance between the evaporator and the compensation chamber.

2. The passive thermal control valve responds to changes in the battery temperature and opens or closes the radiator port within 10 to 15 °C of the set point temperature that is fixed by the backpressure gas. This variation in the valve opening is attributed to the spring constant of the bellows and other unknown effects. If precise thermal control of the current batteries within 1 to 3 °C was desired, this valve may not be suitable in the current configuration for low power VCLHP applications.

3. The single compensation chamber LHP operates satisfactorily in different adverse orientations of compensation chamber with respect to the evaporator for low power operations from 10 Watts up to 30 Watts.

4. The LHP performed satisfactorily during the diurnal simulation of the rover battery system.

The PCM storage unit exhibited the following major characteristics during the tests and analysis conducted to date.

1. The storage unit goes through the freezing and thawing cycles very satisfactorily. All the PCM freezes and thaws around -10 °C. The carbon fiber matrix, dodecane material and the packaging held together very well.

2. The carbon fiber interface material between battery and the PCM canister on one side and the LHP condenser and the battery on the other side provided very good thermal interface with contact conductance of 0.2 to 0.5 W/°C-cm^2.

The battery thermal control system consisting of the above two technologies, VCLHP and PCM storage unit, can meet the Mars '05 rover battery temperature requirements. However, there are some improvements that can be made for the VCLHP design that would enhance its thermal control performance. Currently, a battery thermal control system using the CC heater instead of the thermal valve is being tested to determine the amount of CC heater power that is needed to meet the Mars '05 rover battery temperature requirement. A second VCLHP possible design change would involve reducing the thermal conductance between the evaporator and the CC by reducing the thermal path between them.

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